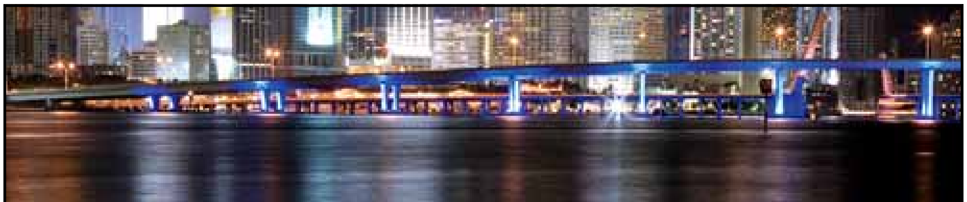


Sustainable IT Ecosystem

Components and Packaging Implications

Chandrakant Patel
HP Fellow and Director
Sustainable IT Ecosystem Laboratory

Objective and Organization

IEEE CPMT Talk, February 26, 2009

Components and Packaging Technology necessitates systemic viewpoint

<u>Sustainable IT Ecosystem</u>

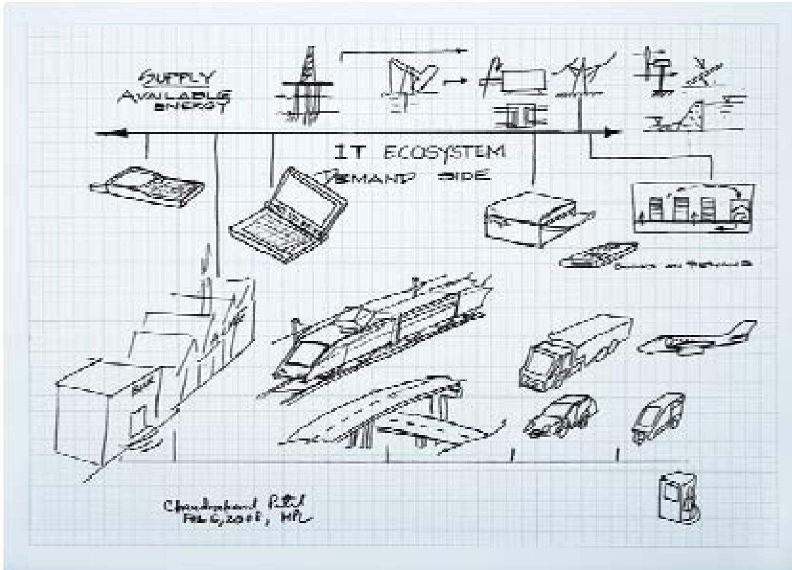
- IT ecosystem can enable sustainable transformation
    - Deconstructing conventional business models through IT services
    - Need based provisioning of resources
  - Data centers at the core, billions of service oriented client devices at the edge
    - Universal accessibility will require reducing the Total Cost of Ownership
    - TCO reduction will require “cradle to cradle” least energy, least material solutions

<u>Components and Packaging design must take a system perspective</u>

- End to End Design
  - Least Energy
    - Examining the performance of the ensemble
  - Least Material
    - Through lifecycle engineering and management

Sustainable IT Ecosystem

billions of service oriented client devices and thousands of data centers….to deliver net positive impact



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Sustainable IT Ecosystem

Approach

- **Next Generation Infrastructure - City 2.0**
  - Supply and Demand Side Management to meet the needs of the inhabitants
    - Supply Side:
      - Need to design the physical infrastructure with lifecycle engineering – energy required in extraction, manufacturing, operation and reclamation – in mind, so that the embedding of available energy into the built environment can be minimized
      - Need to utilize local resources to minimize destruction of available energy in transmission, construction of transmission infrastructure, etc
    - Demand Side:
      - Provision fundamental resources based on the needs of the user
      - Can available energy from 2nd law be used to represent resources
- **Use the IT Ecosystem to enable supply and demand side management based**

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Delivering Net Positive Impact through Supply and Demand Side Management

- Deconstruct conventional business models and replace with lower carbon IT services
  - *Advantage of scale when billions utilize IT to address their fundamental needs and improve quality of life*
- Transformation necessitates
  - Reducing the cost of IT for universal accessibility
    - Reducing TCO necessitates addressing sustainability with an end to end perspective
- Use the IT ecosystem to enable need based provisioning of resources across all ecosystems
  - Transformation necessitates
- pervasive sensing, knowledge discovery, and control
- *Key Enablers:*
  - *Tools & Unifying Metric*
  - *Return to fundamentals of Physical Engineering in combination with Computer Science*
  - *Human capital trained in the fundamentals – multidisciplinary curriculum*

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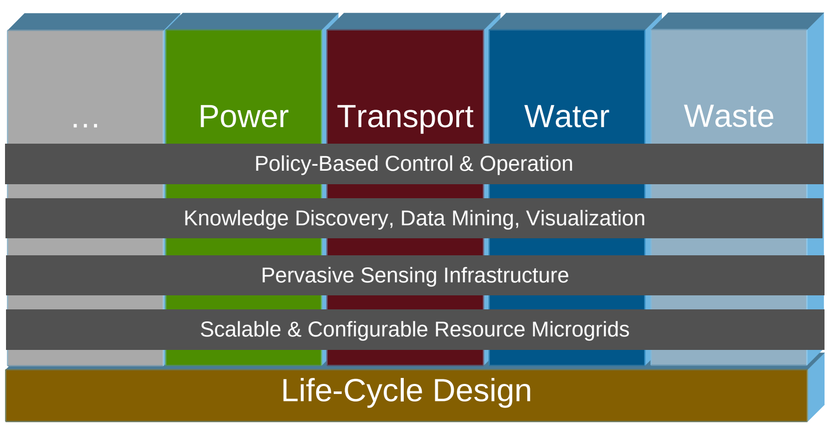
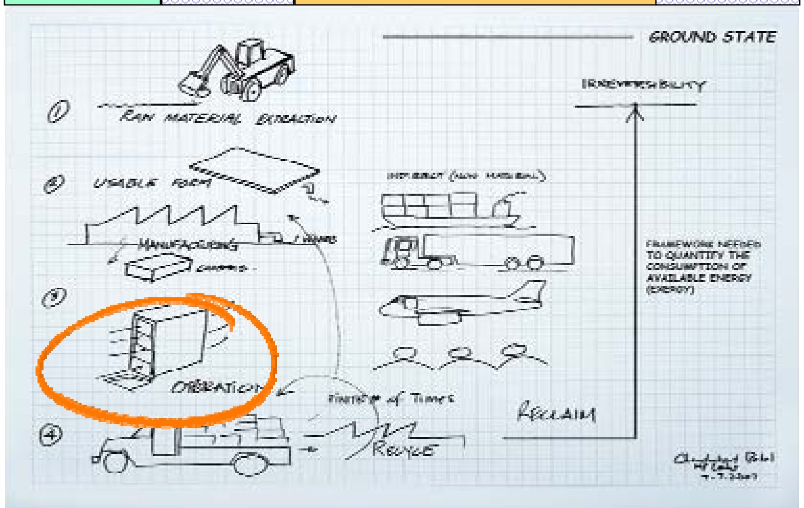
City 2.0 Architecture



Tools for Sustainable Transformation

metrics for least energy, least material ecosystems

extraction	manufacturing	operation	End of Life

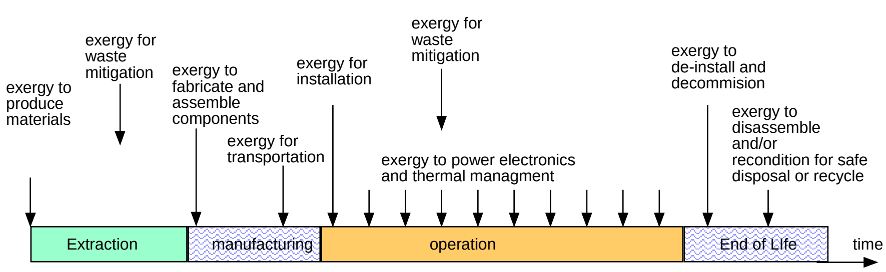


Approach

2[nd] Law of Thermodynamics

- Can a measure of the total exergy or available energy destroyed across a product's lifetime ("lifetime exergy") be a measure of the environmental sustainability?
- Can we build a "hub" of exergy data to enable lifetime exergy analysis for a given product?

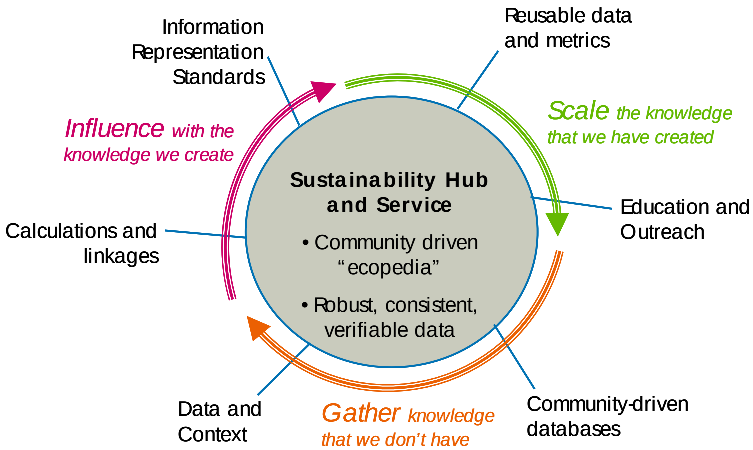
Joules of Exergy consumed becomes the currency of the Sustainability Age



Sustainability Hub

Community-Owned Resource for Knowledge Sharing

- **Influence**, **gather**, and **scale** knowledge within the global sustainability community to enable an open-source service



Exergy: Water example

(ref. SANDIA/DOE)

Energy consumption	Average per million gallons
Water Treatment	0.25MWh
Water distribution	1.3 MWh
Waste Water Treatment	2.5 MWh
Desalination	20 MWh

(Ref. California Energy Comission)

Average per capita usage in the USA: 100 gallons per day

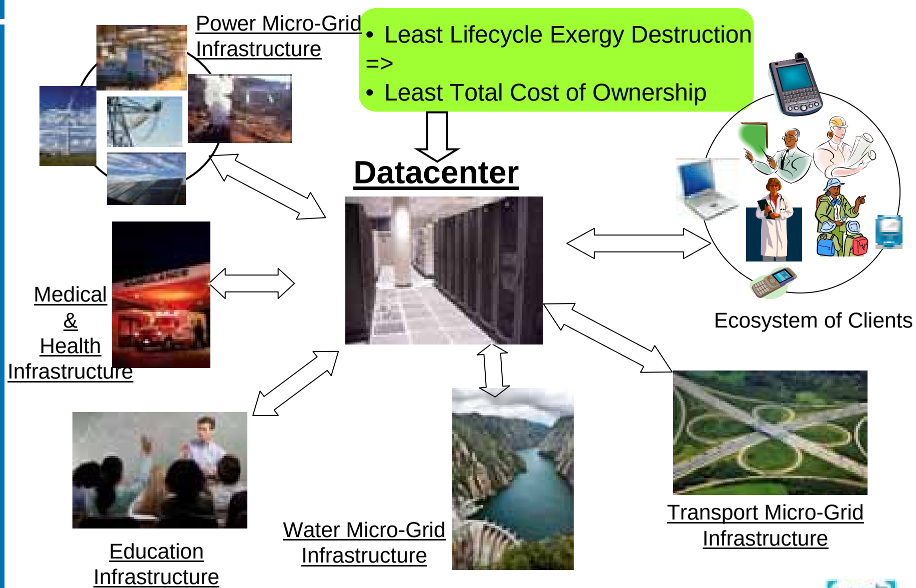
Total (excluding desalination)	~ 0.5 GWh to serve a city of a million per day

$$Water_{index} = \frac{\text{(Energy Consumed in Direct water usage and Indirect water usage)}}{\text{(Energy Consumed by Process)}} \times 10^3$$

Sharma et al., "Water Efficiency Management in Data Centers: Introducing a Water Usage Energy Metric", International Conference on Water Scarcity, Global Changes and Groundwater Management Responses, Irvine, CA, December, 2008

Role of the IT Ecosytem

Supply and Demand Side Management at City Scale



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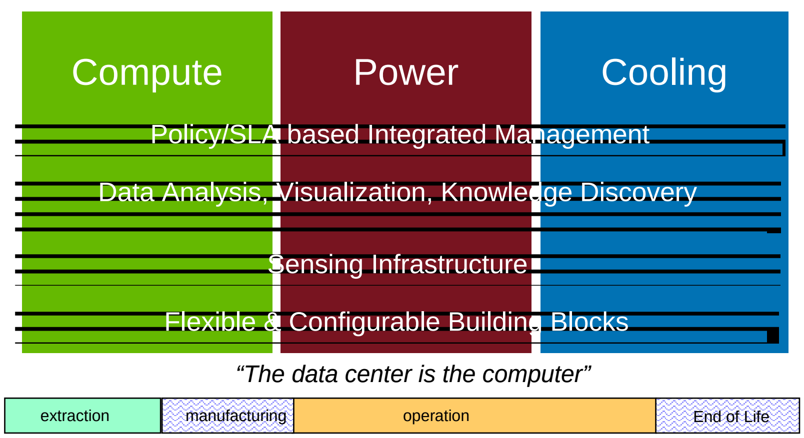
Sustainable IT Ecosystem Lab, HP Labs, 2008

Architecture for a Sustainable Data Center

End to end design and management



- *Data Center Synthesis using end to end analysis Tools*
- *End-to-end Management* using requirements derived from service level agreements (SLAs) and a flexible infrastructure that can be closely monitored and finely controlled

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Part 2

Summary of Part 1

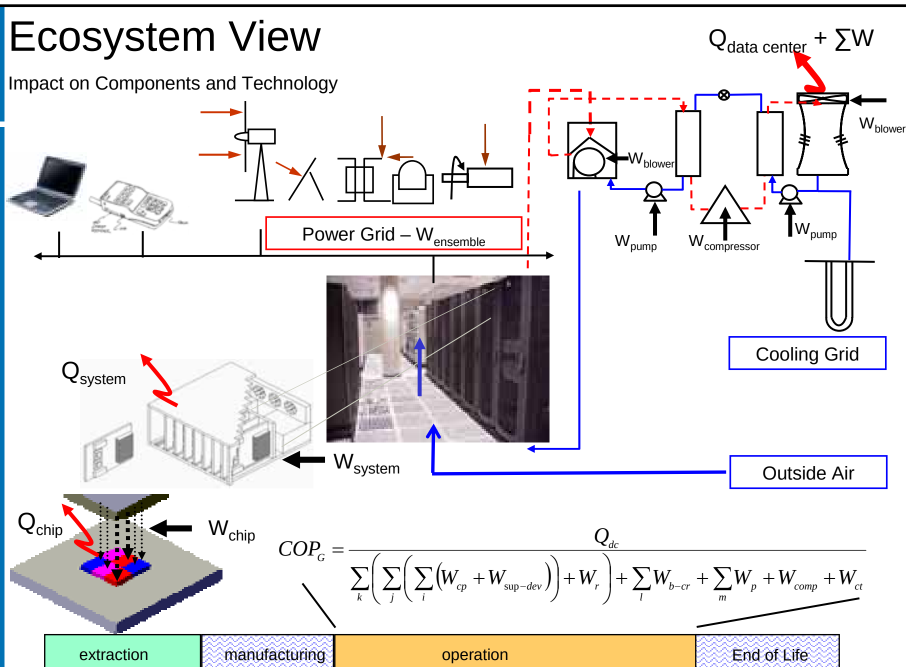
- **Sustainable IT Ecosystem**
  - Enabling next generation of communities: City 2.0
  - Role of the IT Ecosystem
    - *Services*
    - *Need based Provisioning through supply and demand side management*
- Introduced Unifying "Cradle to Cradle" Metric based on the 2nd Law of thermodynamics
- Supply and Demand side management centered around the core – a data center
- Physical representation of data center as a system: ***"data center is the computer"***

Part 2: Components & Technology Implications

- Implications for components, and packaging technologies given the cradle to cradle systemic perspective of the ecosystem
  - Reduce available energy consumed in operation
    - Reduce available consumed by the devices during operation
    - Reduce available energy consumed in supporting the operation of the devices e.g. cooling
  - Reduce available energy embedded in devices
    - Introducing "exergo-thermovolume" metric for components

Ecosystem View

Impact on Components and Technology

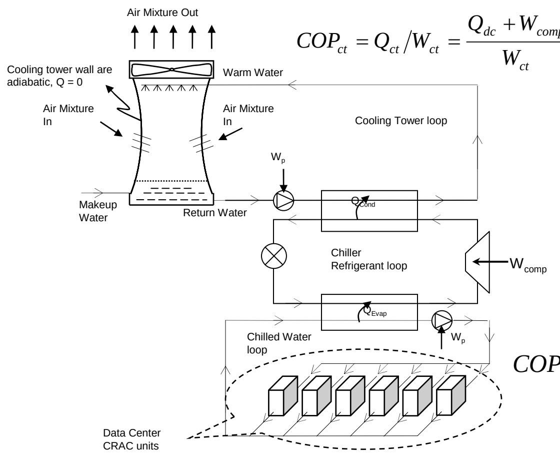


$$COP_G = \frac{Q_{dc}}{\sum_k \left(\sum_j \left(\sum_i \left(W_{cp} + W_{sup-dev} \right) \right) + W_r \right) + \sum_l W_{b-cr} + \sum_m W_p + W_{comp} + W_{ct}}$$

Coefficient of Performance of the Ensemble

$$COP_G = \frac{Q_{dc}}{\sum_k \left(\sum_j \left(\sum_i \left(W_{cp} + W_{\sup-dev} \right) \right) + W_r \right) + \sum_l W_{b-cr} + \sum_m W_p + W_{comp} + W_{ct}}$$

$$COP_{ct} = Q_{ct} / W_{ct} = \frac{Q_{dc} + W_{comp}}{W_{ct}}$$



$$COP_{ch} = \frac{Q_{ch}}{W_{comp}}$$

$$W_{comp} = \frac{\dot{m}_{ref} n P_2 v_2}{\eta_p \eta_{motor} (n-1)} \left[\left(\frac{P_3}{P_2} \right)^{(n-1)/n} - 1 \right]$$

$$COP_{hydronics} = Q_{dc} \Big/ \sum \left(W_p \right)_{secondary}$$

Patel, C.D., Sharma, R.K., Bash, C.E., Beitelmal, M, "Energy Flow in the Information Technology Stack: Introducing the Coefficient of Performance of the Ensemble", ASME International Mechanical Engineering Congress & Exposition, November 5-10, 2006, Chicago, Illinois

Impact on Data Center Total Cost of Ownership

Sustainability through end to end design and management => Least Cost

$$Cost_{total} = \left(\frac{\$}{ft^2} \right) \left(A_{critical}, ft^2 \right) + \left(1 + K_1 + L_1 + K_2 L_1 \right) U_{\$,grid} P_{\substack{consumed \\ hardware}} + R \left(M_{total} S_{avg} + IT_{dep} + \sigma_1 \right)$$

Real Estate — **Burdened power consumption** — Personnel, equipment, SW per rack

J_1 : capacity utilization factor, i.e. ratio of maximum design (rated) power consumption to the actual data center power consumption

$K_1 = F(J_1)$: burdened power delivery factor, i.e. ratio of amortization and maintenance costs of the power delivery systems to the cost of grid power

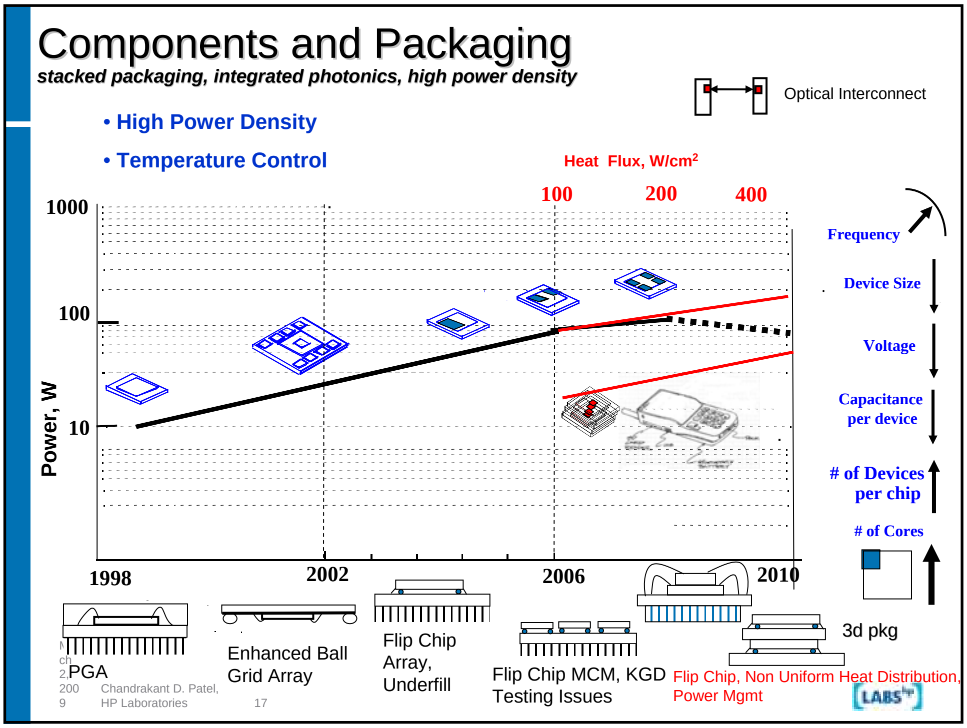
$K_2 = F(J_1)$: burdened cooling cost factor, i.e. ratio of amortization and maintenance costs of the cooling equipment to the cost of grid power

Depreciation factors

L_1: cooling load factor, i.e. ratio of power consumed by cooling equipment to the power consumed by compute, storage and networking hardware (inverse of $COP_{ensemble}$)

extraction	manufacturing	operation	End of Life

Patel and Shah, Cost Model for Planning, Development and Operation of a Data Center
http://www.hpl.hp.com/techreports/2005/HPL-2005-107R1.html


Components and Packaging
stacked packaging, integrated photonics, high power density
Optical Interconnect
• High Power Density
• Temperature Control
Heat Flux, W/cm²
100
200
400
1000
100
10
Power, W
Frequency
Device Size
Voltage
Capacitance per device
# of Devices per chip
# of Cores
1998
2002
2006
2010
PGA
Enhanced Ball Grid Array
Flip Chip Array, Underfill
Flip Chip MCM, KGD Testing Issues
3d pkg
Flip Chip, Non Uniform Heat Distribution, Power Mgmt
Chandrakant D. Patel, HP Laboratories
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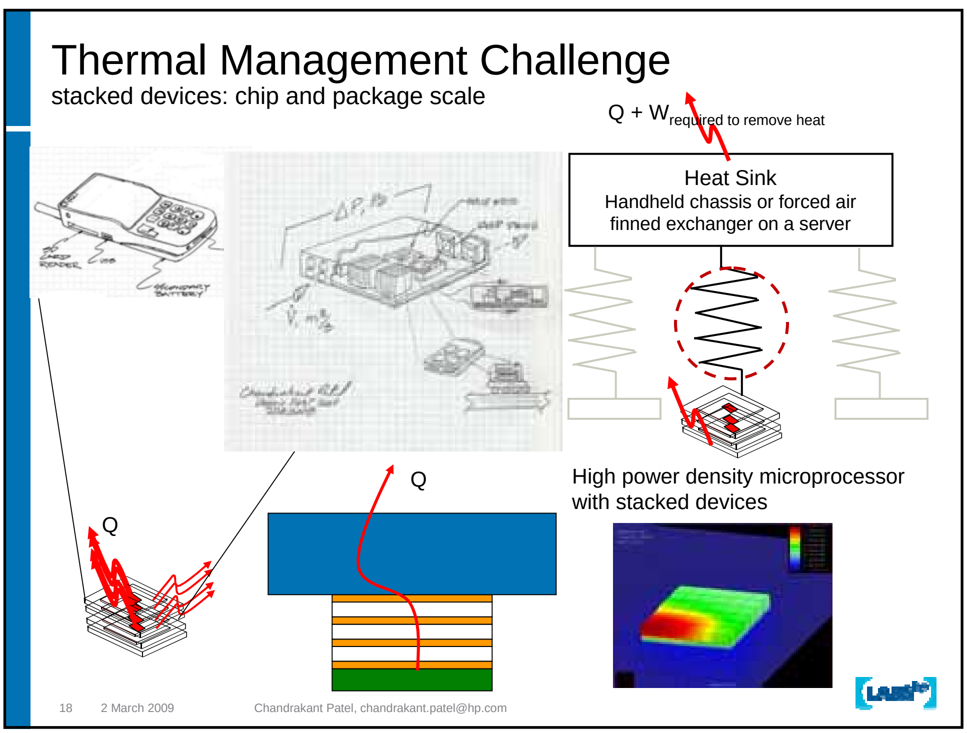
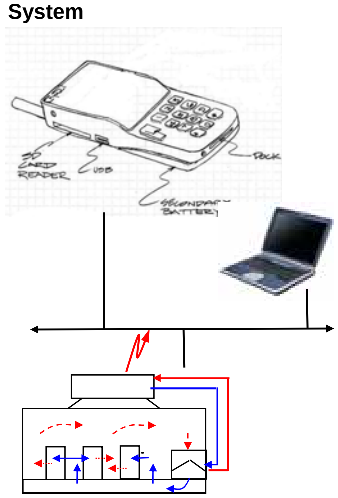

Thermal Management Challenge
stacked devices: chip and package scale
Q + W required to remove heat
Heat Sink
Handheld chassis or forced air finned exchanger on a server
Q
Q
High power density microprocessor with stacked devices
18
2 March 2009
Chandrakant Patel, chandrakant.patel@hp.com

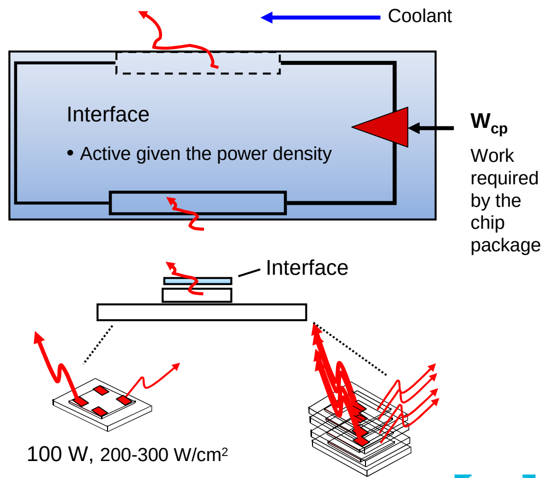
Active Cooling at Package Level

Demise of Passive Only Cooling Solution

System



Component & Package



Work Required at Package Level

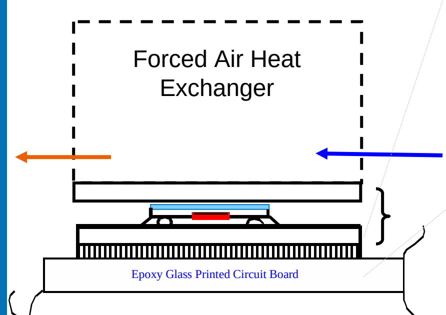
High Power Density Chips

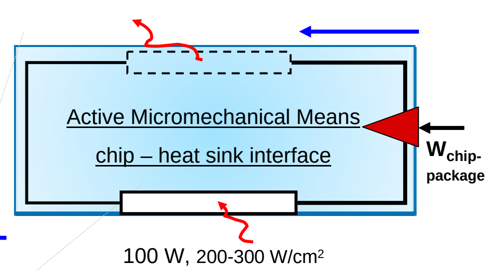
Fan Work: 4 W

~.008 m³/s, ΔP of 75 Pa; $\zeta_{\text{wire to air}}$: 15%

TEC Interface Chip Package Work: 30 W

$W_{\text{chip-package}}$ ~ 30 W (COP of 3 for ΔT of15 C)





Thermo-electric Module

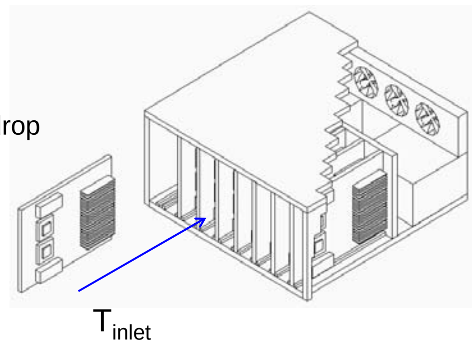
30 W for a 15 °C of temperature reduction between hot and cold side

34 W of Power Required by Cooling Resources to remove 100 W

Flow Work & Thermodynamic Work

Work required to remove heat:

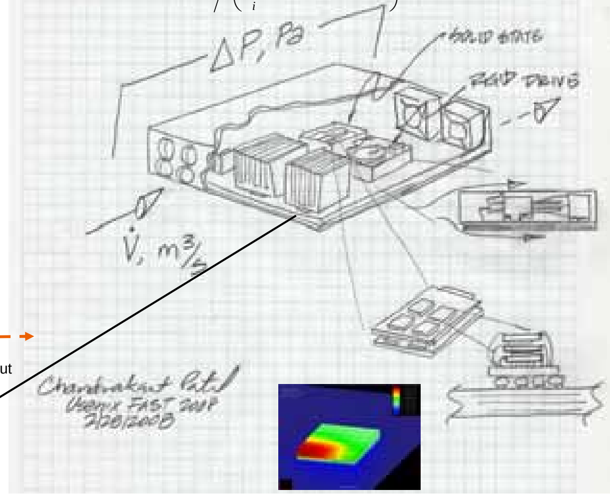
- Flow & Thermodynamic Work
  - Flow Work
    - Volume flow and pressure drop
      - *volume flow, m^3/s*
      - *pressure drop, Pa*
  - Thermodynamic Work
    - *Temperature, °C*

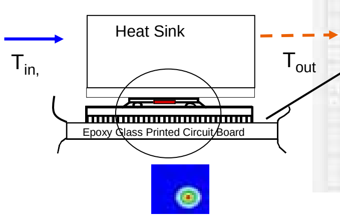


Available Energy Consumed in Heat Removal

Work required to remove heat from chip and system enclosure

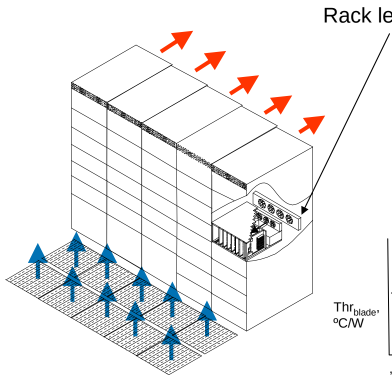
$$COP_{sys} = \frac{Q_{sys}}{W_{sys}} = \frac{\sum (Q_{cp} + Q_{\sup-dev})}{\sum (W_{cp} + W_{\sup-dev})} = \left(\dot{m}_a C_{p,sys}\left(T_{in,sys} - T_{out,sys}\right)\right) \Big/ \left(\sum_i \left(W_{cp} + W_{\sup-dev}\right)\right)$$





Operation

Work Required at Rack Level



System active cooling device e.g. blower

$$COP_r = \sum_i Q_{sys} \Big/ \left(\sum_i W_{sys} + W_r \right)$$

System Flow Work determined from volume flow and pressure drop

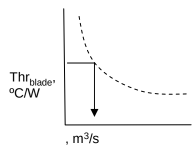


Fig 5c. Thermal Resistance

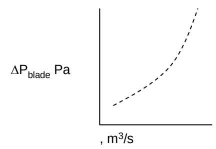


Fig 5d. Volume Resistance

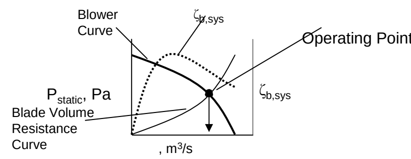
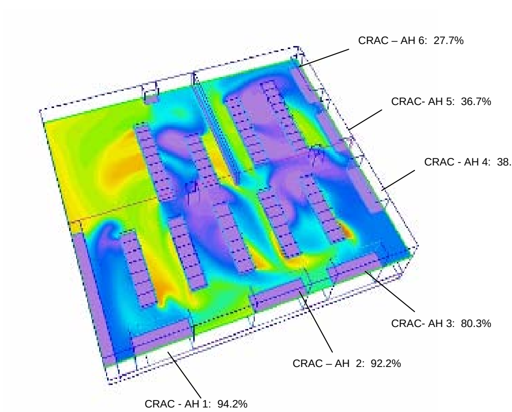
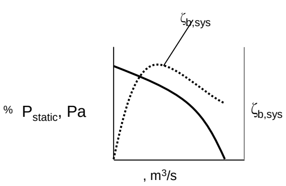


Fig 5e. Blower Characteristic Curve

Computer Room Air Conditioning Unit (CRAC)

Example shown has a Chilled Water Air Handling Unit in the room – so we will refer to it as CRAC – AH (Contains Air Mover and a Chilled Water Coil)





Blower Characteristic Curve

$$\left(COP_{cr}\right)_l = Q_{cr} / W_{b-crah}$$

COP of Ensemble

$$COP_G = \frac{Q_{dc}}{\sum_k \left(\sum_j \left(\sum_i \left(W_{cp} + W_{\sup-dev} \right) \right) + W_r \right) + \sum_l W_{b-cr} + \sum_m W_p + W_{comp} + W_{ct}}$$

$$Cost_{total} = \left(\frac{\$}{m^2} \right) \left(A_{critical}, m^2 \right) + \left(1 + K_1 + \frac{1}{COP_G} + K_2 \frac{1}{COP_G} \right) U_{\$,grid} Pwr_{consumed,hardware} + R_a \left(M_{total} S_{avg} + IT_{dep} + \sigma \right)$$

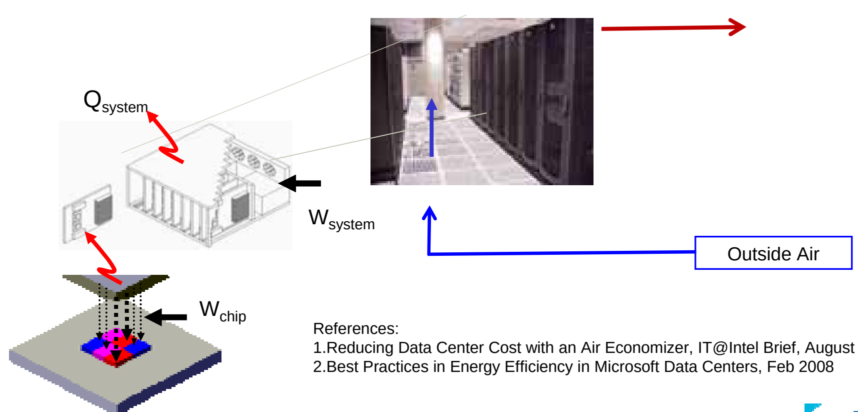
- Representing L_1 as inverse of COP_G

Reducing the Cost of the Data Center

Maximizing COP_G

System Consideration: Using outside air i.e. eliminating the chiller in the ensemble

- Component design drives this upstream consideration
- Need to revisit environmental specifications with lifecycle in mind
- In face of challenges: high power density, optical interconnects, stacked die



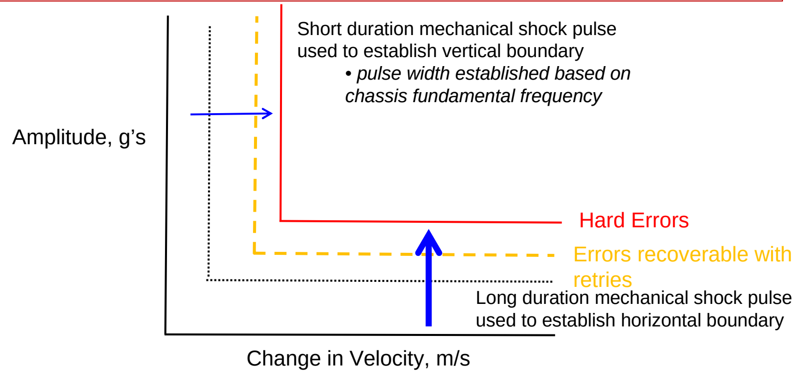
References:
1.Reducing Data Center Cost with an Air Economizer, IT@Intel Brief, August 2008
2.Best Practices in Energy Efficiency in Microsoft Data Centers, Feb 2008

Revisiting Environmental Specifications

Components need a "Damage Boundary" specification with respect to temperature

Drawing the analogy from late 1980s - "damage boundary" technique used to assess fragility of a disc drive to mechanical shock [3][4].

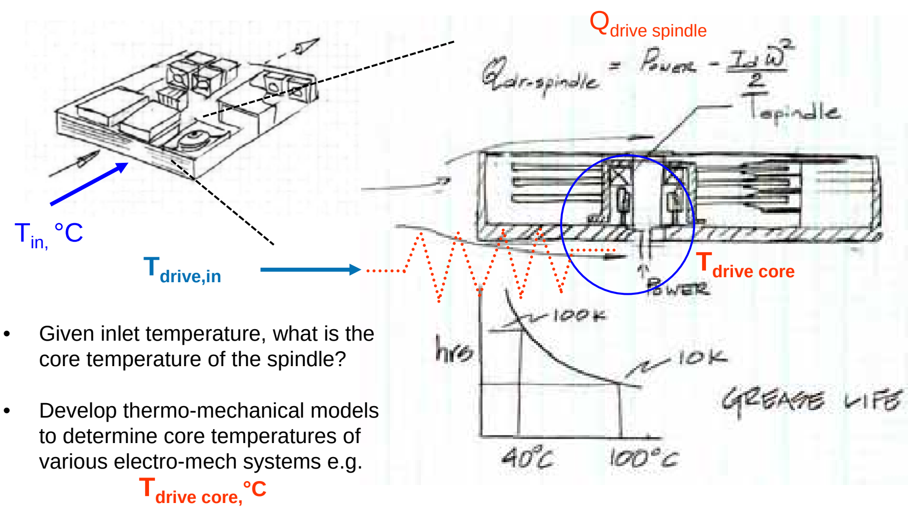
1. Is there an analogous approach to establish temperature "damage boundary" for components?
2. What is the lifecycle impact?



[3] Hedtke, L and Patel C.D., Damage Boundary Assessment of Hard Disc Drives, ASME WAM 1990
[4] Newton, R.E., "Damage Boundary Revisited", Technical Report 89-WA/EEP-24

Thermo-mechanical Models to assess Damage

end of life prediction



- Given inlet temperature, what is the core temperature of the spindle?
- Develop thermo-mechanical models to determine core temperatures of various electro-mech systems e.g. $T_{drive\ core}$, °C

extraction	manufacturing	operation	End of Life

Design Approach

Lifecycle Based Engineering and Management

Cradle to Gate

Focus on embedded exergy

Sensors for roadbeds:
Performance requirement not changing with time, no need to upgrade for a long period
• resistant to wide environmental requirements
• ideally passive or low power requirement

Data Center, system chassis e.g. rack

Gate to Grave

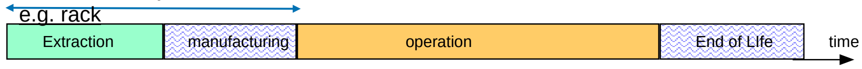
Focus on operational exergy

Servers for core data centers:
Performance improvements allow more users per processors e.g. three year upgrade cycle for a microprocessor
• Library of hybrid active-passive solutions
  • scalable power and cooling solutions

Grave to Cradle

Focus on embedded exergy

• appropriate material choices to enable reclamation
• appropriate material choices to enable operation at elevated temperatures



Key Message

IEEE CPMT Talk, February 26, 2009

- Need for a systemic viewpoint in Components and Packaging
  - Computing is at the crossroads
    - Early days of computing saw vertically integrated organizations building computing solutions
    - Commoditization of compute hardware created an ecosystem of suppliers of hardware and software
      - Computing solutions were integrated in place
      - Data Center became the Computer
    - Now there is an emergence of computing services – Cloud Computing
    - Purveyed from data centers
      - Growth will come from billions who want to use services to improve the quality of life
      - Growth will come from IT becoming seamless with physical infrastructures such as cities
  - Component designs are affected by upstream and downstream considerations

Joules: Currency of the Sustainability Age

ecosystem: billions of handhelds and printers, thousands of data centers and print factories